Renewable and Sustainable Energy Reviews 28 (2013) 500–509

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Sustainable energy planning: Leapfrogging the energy poverty gap in Africa ☆

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A R T I C L E I N F O

Article history:
Received 5 March 2013
Received in revised form
2 August 2013
Accepted 11 August 2013
Available online 2 September 2013

Keywords:
Optimisation
Renewable technologies
Photovoltaics
Mini hydro
Rural electrification

A B S T R A C T

The present paper introduces the results of a spatial-economic analysis that identifies the least cost rural electrification options that can bring the persistent energy poverty to an end in Sub Saharan Africa. The rationale behind the analysis is that the applicable energy technologies have gone through fundamental changes and these have profound effects on the competitiveness of the various options.

The least cost distributed generation options are calculated for each geographical location for mini hydro, off grid PV and diesel generators options and it is compared to the electricity grid extension. The methodology presented in this manuscript organises the scarcely available energy-related local and regional geo-information into comprehensible maps. The set of tools presented and the results based on those analyses can support decision and policy makers to plan for the least-cost rural electrification options while also adapting to the most effective way to reduce energy poverty. This can help in the national rural electrification plans by delineating which communities cannot be reached by existing grid without excessive extension costs and gives the alternative distributed generation option.

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.08.044

1. Introduction

More than 1.6 billion people lack access to electricity, and another billion suffer intermittent or marginal quality of service. The majority of these people live in peri-urban or rural areas of sub-Saharan Africa and South Asia. If current strategies to increase access to modern energy systems are maintained, electrification rates will continue to diverge significantly among regions. While levels of electricity access in Latin America, the Middle East and North Africa are generally over 80–90%, sub-Saharan African countries are struggling to escape from "energy poverty" with nearly 70% of their population lacking access to electricity [1].

The energy sector of the developed world reached near 100% electrification levels decades ago, but the sector faces new challenges. In this part of the world, energy development is aimed at accelerating the decarbonisation process [2]. Reduction of the global environmental impacts of energy services are reflected in an increasing efficiency, diminishing energy intensity and diversifying the energy mix through a rapid deployment of renewable sources. As a result of the increasing market shares for renewable energy and energy-efficiency technologies, their high up-front investment costs have decreased dramatically [3].

In contrast, in the last 20 years, the traditional approaches to electrify sub-Saharan Africa (installing large size power plants and extending the grid to new consumers) have neither contributed to the eradication of rural poverty nor have they reached the targets set-up in the United Nations' Millennium Development Goals (MDGs). A reliable source of energy is clearly needed to fuel development in sub-Saharan Africa. In fact, U. N. Secretary General Ban-ki Moon has designated 2012 as the "International Year of Sustainable Energy for All" (SE4ALL). The significant attention that has gone to the goals, calls for a new cross-cutting MDG that set more ambitious targets in access to electricity by 2030.

The conventional approach to electrification is not always appropriate, and certainly not going to happen in a timely fashion for many sub-Saharan communities. Many of these communities will consume only small amounts of electricity and it is doubtful that the costs of extending the grid can be recouped. The grid system in many African nations is also in urgent need of refurbishment and it makes no sense extending an unreliable resource to remote communities [4].

Distributed technologies have often been considered in rural electrification plans in sparsely populated areas, but in Africa they have rarely been applied despite the fact that Africa has the highest proportion of population living in dispersed areas. Even the latest rural electrification master plans are dominated by the grid extension options and the often negligible segment of distributed generation is typically diesel genset [5]. However, the last five years have shown unprecedented development in electricity production technologies. On one hand the photovoltaic solar technologies are deployed at unparalleled capacity levels, and at steeply decreasing production costs. On the other hand more and more governments need to reduce their generous fossil fuel subsidies. New mini hydro technologies make it possible to provide services on rivers where it was not feasible before.

Based on this formulation of the problems, we have tried to define some important policy research questions concerning the rural electrification in Africa as the following:

- Could decentralised energy systems be the answer to the challenge of providing universal energy services in Africa in the medium term?
- Just as many African communities have leapfrogged landline telephone technology by adopting mobile phone technology instead, could sub-Saharan African communities benefit from locally generated electricity in decentralised networks?

The analysis focuses on the key challenge for developing electricity services in sub-Saharan Africa [2,3,6,7] and assesses the role that decentralised systems can play. A set of spatial analysis tools is used to estimate and visualise the price-competiveness sensitivity of rural electrification options to global energy price change, using as an example the evolution of the least-cost off-grid option (diesel vs. PV). We also discuss long-term solutions that could support the required African energy technology revolution by leapfrogging to flexible technologies (decentralised systems) in place of fixed infrastructure technologies. We highlight a unique opportunity to effectively energise sub-Saharan Africa without repeating developmental stages seen in the developed world (i.e. installation of large-scale, centralised power plants and grid extension).

Africa has a vast untapped renewable energy potential, which could be used in an environmental-friendly way to meet Africa's energy demands several times over [6]. The "energy access problem" is not, in fact, due to a lack of energy resources but rather to a combination of financial, political and sociological challenges related to the development of local energy resources [2]. Despite its large population – exceeding one billion in 2009 – most parts of the African continent are sparsely populated, with almost 60 per cent living in non-urban areas [7]. This fact, coupled with low per-capita energy consumption, the high proportion of non-electrified rural population and the urgent need of refurbishment of the grid system [4], creates an ideal context for sustainable energy development based on decentralised renewable energy sources.

The paper is structured in the following way. Following the above described energy framework and its unsustainable trends in sub-Saharan Africa, the research focus was formulated in the introduction. The subsequent chapter defines the scope selection of the feasible technology options. Due to the lack of conventional statistics in the energy domain in Africa a novel comparative methodology is introduced in Section 3, based on the most up-to-date technology costs using GIS and satellite input data. This chapter assesses the competitive potential of alternative energy technologies (PV, mini hydro, diesel gensets) to grid extension. The techno-economic analysis identifies the least cost energy options for each location in Africa (see also Fig. 1). Section 4 sums up the financial framework conditions set by the International Development Organisations to meet the projected energy needs in Africa. Section 5 draws attention to the still available power generation portfolio options to reduce the overall costs and reach the poorest with the energy services: the decentralised power generation options relying on local renewable sources. By setting up this alternative portfolio it also identifies the economic barriers (i.e. fossil fuel subsidies) and determining social factors on technology choice (i.e. the effects of population density) and the paper concludes with ensuing financial and policy implications how to reach convergence by leapfrogging the energy difference.

2. Scope of the study: the selected rural electrification technology options

There are number of technological options that can be applied in rural electrification [3,6–8]. In a previous paper [9] the authors have presented a methodology for comparing PV- and diesel-based rural electricity generation options with the grid extension. Following this study, the authors have surveyed AFRETEP members [10] (a platform managed by the JRC with more than 700 African and other energy research stakeholders) and the 94 participants of the African regional capacity building workshops [11] and the analysis was extended according to the expressed preferences. Wind, geothermal and biomass based technologies

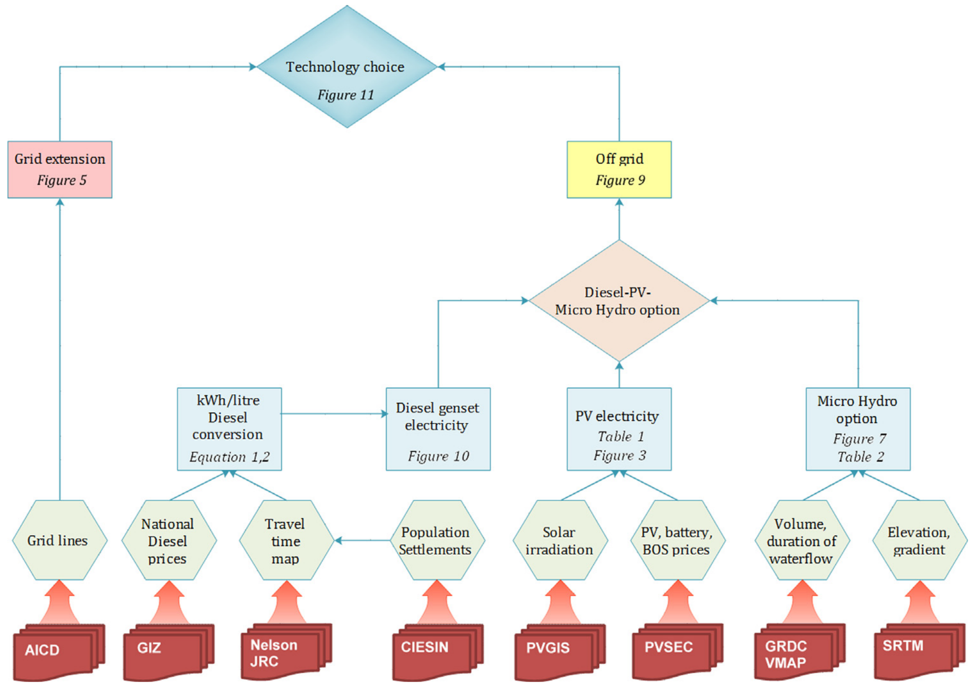

Fig. 1. Logical framework of the applied methodology, indicating the relevant equations, tables and figures (see in the following chapters) of the developed model.

Table 1
The input PV parameter changes between the 2011 and the present analyses.

PV module cost (€/kWp)	Rest of the system (€/kWp)	Battery costs (€/Ah)	Battery, life time (years)	O&M costs
Analysis based on 2010 data				
2500	1000	1.5	5	2.5%/year of PV array
Analysis based on 2012 data				
1100	800	1.5	4	2.5%/year of PV array

were mentioned as potential choices but the mini hydro option was ranked as the most suitable option for rural electrification. Later this analysis shows that is quite complementary to the PV options: it is available in many places of Sub-Saharan Africa where stable cloud cover reduces solar irradiation. Wind will become a potentially important technology in hybrid systems, however the latest studies point out that off grid application need high investment subsidies and functioning feed-in-tariff systems in order to become competitive with other options [8]. The most advanced technology and resource availability maps are presently available for grid connected wind generators [12,13]. High resolution wind maps of 10–20 m height are not available. Existing geothermal-based electricity generation capacity has almost exclusively been grid connected large scale applications as the high investment costs and exploration risk could be secured only by the economy of scale. UNEP proposes to accelerate the development of geothermal resource potential in Africa using the East African Rift example, emphasising the large scale advantages [14]. Presently bioenergy sources are mostly used for other energy purposes in Africa (fuelwood, heating, biodiesel) but fuel wood shortage is increasing in many countries [15]. The unsustainable uses of the available biomass requires further research on the remaining potential for small scale bioelectricity generations options. Locally produced biodiesel could be used as a substitute fuel in diesel gensets [16]. However, geospatial data on biodiesel potential or availability are not yet available on a continental scale. For these reasons, bioenergy options will not be considered in this study.

In addition to introducing the analysis of small hydro plants, the solar and diesel options have been updated using the latest information on system and fuel prices. This has allowed a more precise comparison of electrification options in Africa. New input data were introduced in the following:

- The latest retail diesel prices by countries [17];
- Extended network including lines close to realisation (mainly in case study countries);
- Updated technology costs for PV: as a result of the dramatic reductions of system prices observed in the global market between 2010 and 2012. The model for off-grid PV system performance has also been updated, mainly using hourly solar radiation data instead of daily data.

The input variables are summarised in Table 1.

3. Mapping electrification costs of distributed systems

For the analysis of the different energy options, a spatial electricity cost model has been designed to point out whether diesel generators, photovoltaic systems, small hydropower plants or extension of the existing transmission line could provide the least-cost option in off-grid areas.

The developed compound application uses a methodology that is customizable and expandable, which allows a comprehensive, spatially explicit techno-economic analysis. The multi-layered methods include spatial analysis and mapping that use the global and regional databases derived by functions of remote sensing, geographic information systems (GIS) modelling, satellite image processing and processing of long-term meteorological data. Geo-referenced data systematically collected on grid network, travel times to major cities based on transport network model, attributes of populated places and a derived dataset of permanent river courses have formed the boundary conditions of the model [18]. The methodology applies a novel approach to assess small hydro energy potential by using elevation and river network data previously employed in flood forecasts; satellite images

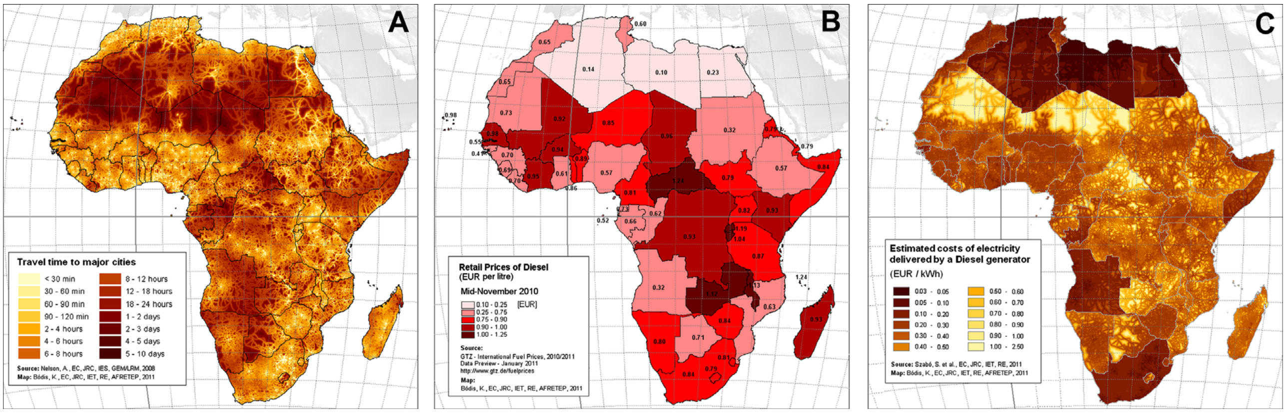

Fig. 2. (a–c) Geographic representation of the input data (a: travel time b: diesel price) and the estimated cost distribution (c) resulted by the model. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

of insolation to model solar energy production potential (as solar irradiation measurement is almost completely lacking in Africa). The off-grid diesel electricity cost calculations use for each location the travel time proxies [19] with the combination of national diesel prices [20]. The quantified kWh electricity cost for several energy technology options take into consideration the local energy resources and the already existing infrastructure (settlements, road infrastructure, grid, solar irradiation, river flows, river basins). The method uses the latest data on technology and costs of micro-hydro, diesel and standard PV to calculate the cost of electricity generated. Then, based on the kWh costs, the methodology finds the least-cost mini-grid production costs option for each location in Africa. It also compares these with the national grid electricity costs (including standard extension costs) [9,20,21].

3.1. Calculation the electricity production costs from diesel generators

By using the below described methodology, from the input data on global map of accessibility developed by the JRC [19] (Fig. 2a) and on the international diesel prices available for 2010 [17] (Fig. 2b), the electricity production costs from diesel generators were calculated for each geographic location of Africa.

3.1.1. Estimation of transport costs

The transport costs (€/l), P_t, for diesel are estimated using the following equation:

$$P_t = 2P_d ct/V \tag{1}$$

where P_d (€/l) is the national market price for diesel; c (l/h) is the diesel consumption per hour; t (h) is the transport time, and V (l) is the volume of diesel transported. The factor 2 is due to the fact that the vehicle has to drive back to the origin point (assuming dedicated transport for the fuel in the generators). For the calculations, we assumed average values of $V = 300$ l and $c = 12$ l/h. These parameters assume the use of a standard small van of a carrying capacity of 300 l. The transport cost is calculated as 0.01 Euro per kWh one way [9,22], with 12 l consumption in 1 h (it can cover different distances during the same period assuming approximately the same consumption per hour depending on the roughness of the surface).

3.1.2. Estimation of production cost for electricity

Production cost for electricity (€/kWh) is calculated as

$$P_p = (P_d + P_t)\eta \tag{2}$$

where P_d (€/l) is the national market price for diesel, P_t (€/l) is the transport costs from (Eq. 1), and η is the conversion efficiency of the generator, with a value of $\eta = 0.286$ l/kWh [18]

3.1.3. Calculation of the final costs using diesel generators

The final costs of electricity consist of the production costs and the costs of labour, maintenance and amortisation. For this, 1 c €/kWh unit costs are calculated using the commercial price and the average lifetime for the 4–15 kW diesel generators [9,23]. The resulting map (Fig. 2c) shows the spatial variance of the electricity costs per kWh delivered by a diesel generator. The electricity cost ranges between 0.30 Euros (dark brown) to 2.4 Euro (light yellow).

3.2. Methodology for calculation off-grid PV based electricity costs

The levelized cost of electricity (€/kWh) was calculated, assuming a certain daily shape of the electricity load pattern. The algorithm used in the calculations takes into account hourly solar irradiation data from PVGIS [24] (from 2009 to 2011), an optimised value of the PV array size and the battery size, and the calculation of the system performance ratio. The assumptions used for the analysis are[1]:

- The size of the system is minimised for a given electricity consumption to guarantee a certain availability of power; i.e. in this analysis, the system was designed not to run out of energy on more than 5% of days;
- The daily energy consumption pattern is such that 1/3 of the energy is consumed during daytime and 2/3 during evening and night, the hourly consumption profile is taken from [25];
- PV array size is calculated for a nominal desired daily consumption, with both PV array size and battery size varying geographically so as to satisfy this consumption;
- The instantaneous system performance ratio is assumed to be 70%, a little lower than typical grid-connected systems, due to the additional losses in the batteries;
- Battery discharge depth is 70%, this assumes specialized solar system batteries (AGM);
- PV lifetime is 20 years, battery lifetime is 5 years;
- PV module and system prices are given in Table 1, which also shows the values used in the previous study.
- Battery prices are estimated as 1.5 €/Ah for 12 V AGM-type lead–acid batteries. The assumed operation and maintenance costs are assumed to be 2.5% of the price of the PV and BOS for each year of operation;
- Cash flow: 5% discount factor.

[1] The performance ratio is the ratio of actual instantaneous power to the ideal power that would be produced if there were no system losses and no performance degradation due to high PV module temperature.

Fig. 3a shows the solar electricity potential, Fig. 3b shows the result of the calculation described above. The calculation was updated using typical 2012 PV module price data (Fig. 3c). The electricity production cost calculated for local mini-grid PV system in Africa ranges from 0.2 up to 0.55 €/kWh.

3.3. Methodology for calculation grid based electricity costs

The geospatial information on the existing electricity lines for transmission and distribution in Sub-Saharan Africa was collected from freely available data sources [4,20,26–28], from databases of regional institutes or from individual experts [18,29]. However, after the data integration, the digital dataset of electricity grid is still not complete (Fig. 4a), with uneven coverage amongst the 48 countries. The country level electricity price for each country was derived from the World Bank African Infrastructure Country Diagnostic statistics [4]. From the tariff categories the small consumer II category has been used (Fig. 4b), as this corresponds to the projected consumption levels for rural populations (Fig. 4c).

The incremental cost due to the network extension depends on many factors; three main parameters are the population density, the electricity load and the distance from the existing grid. The projected consumption per new consumer indicates the extension cost per kWh of electricity consumed. The grid extension costs have been approximated at 2.5 cEur/kWh/km value [30–33]. The proxy value has been used to determine if the grid extension or the off-grid solution could be more economic in the different rural locations. In the case of existing planned grid extensions, the grid

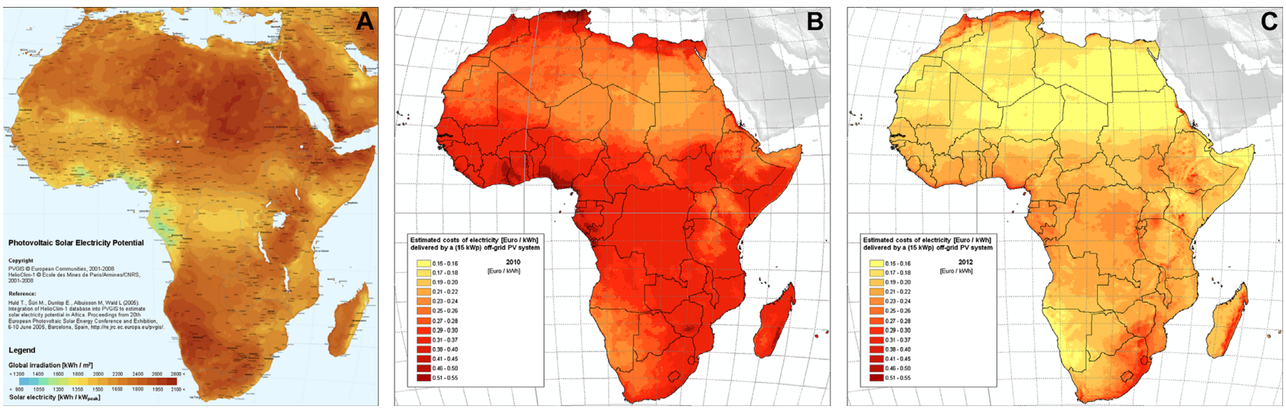

Fig. 3. (a–c) Geographic representation of the solar irradiation input data (a) and the resulting cost distribution for 2010 (b) and 2012 (c).

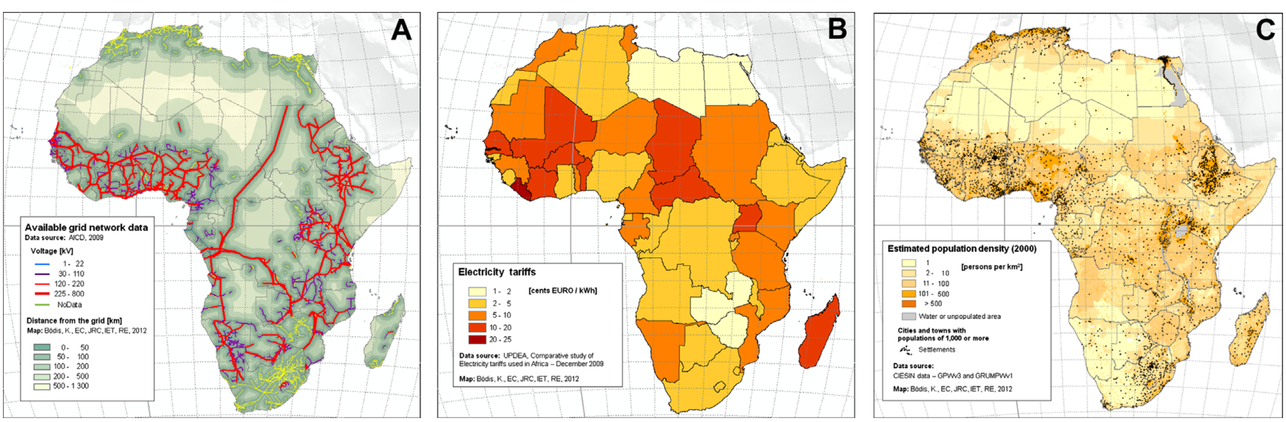

Fig. 4. (a–c) Map of the collected and integrated grid network (a), grid electricity price of single phase domestic usage by countries (b) and population distribution (c).

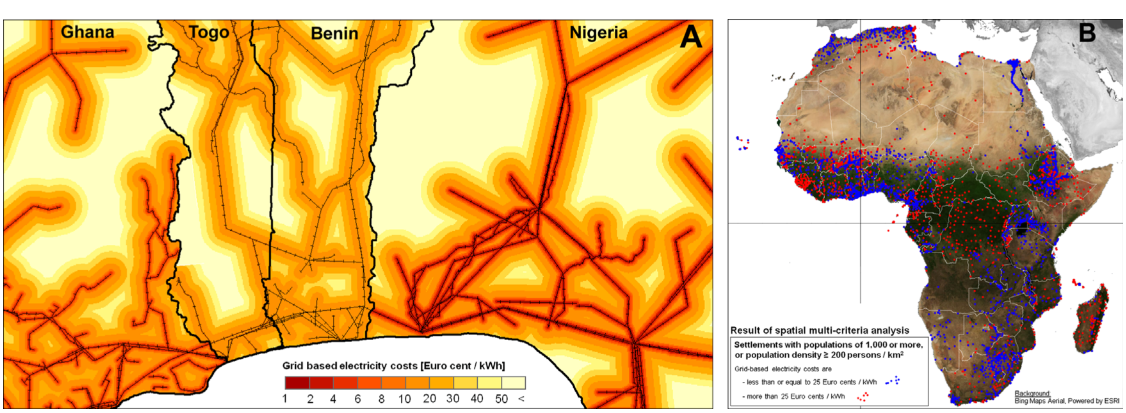

Fig. 5. (a and b) Detail of the map showing modelled linear incremental costs of grid extension (a), results of spatial multi-criteria analysis on extension costs, populated places and population density (b).

infrastructure has been taken as implemented (reaching the most populous regions that are not yet covered).

Fig. 5a shows the linear incremental costs using the cited national electricity tariffs and unified assumption of extension costs. Fig. 5b suggests the grid is already extended to the areas with high population density.

3.4. Mapping potential locations of small-scale hydropower plants

A suitability map of potential hydropower sites has been defined based on four main physical components: distance to permanent water flows, river or surface gradient along the river, size of the catchment area belonging to each section of the river and the mean annual stream flow where it was available.

High quality, integrated and thematically detailed geo-data sets of African water resources are not available. There are subsets of different global databases and local, mostly national spatial data sets. However for the evaluation of the hydropower potentials at continental scale it is essential to work out a harmonised, seamless geometrical layer of the water network with a connected data table describing specific attributes of the water bodies. To evaluate the hydropower potential at continental level, a multi-criteria analysis has been carried out involving the available river data

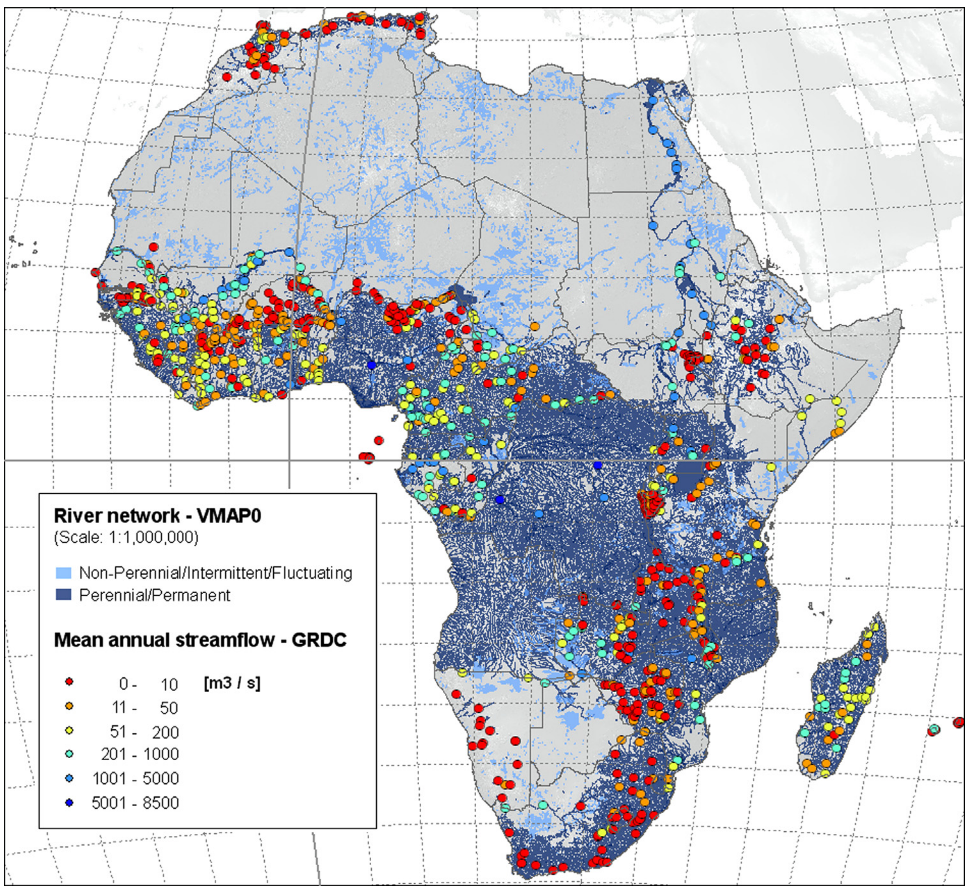

Fig. 6. Geographical distribution of permanent and non-permanent river network in Africa and mean annual streamflow [m^3/s] (a).

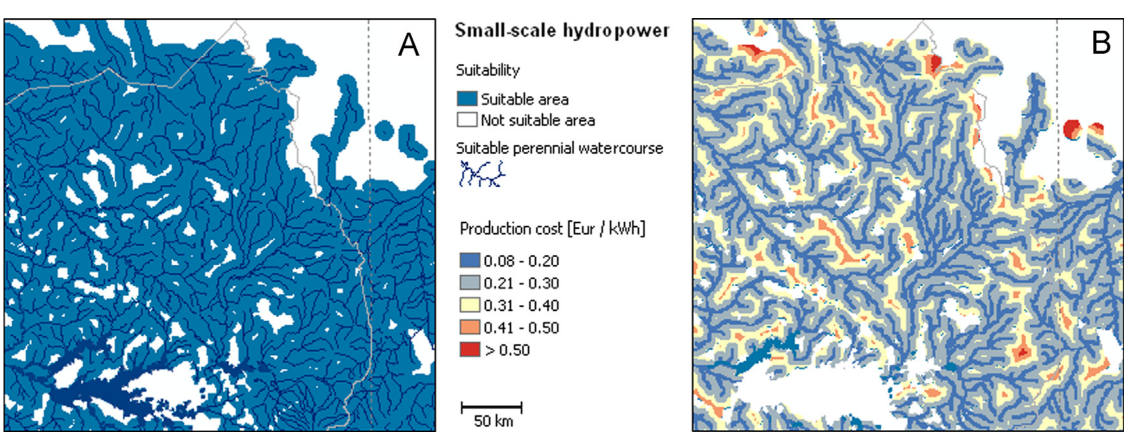

Fig. 7. (a and b) Area suitable for small-scale hydropower plant based on physical conditions (a), differences in electricity production costs based on installation and electricity transmission costs (b).

bases, public global data sources of mean annual river discharge, additional derived information describing the potential flow network and river catchment areas and a high resolution digital elevation model. The elevation model formed the basis for delineation of areas characterised by sufficient surface and river gradient. Technical specifications of mini-hydro turbines as boundary conditions and economic parameters have been applied to estimate the costs of system installation and operation.

3.4.1. Data sources

The Vector Map Level 0 (VMAP0) data provides worldwide coverage of geo-spatial data and is equivalent to a small scale map (1:1,000,000). This data formed the basis of the river courses map and shows the most important descriptive hydrographical information. The source of more detailed information on river regime is the publicly available international archive of river discharge data from the Global Runoff Data Centre (GRDC) (Fig. 6). These data sets were combined with the WaterSHED data, which depicts all linear downflow as 'river course' where the modelled upstream catchment area is more than 1000 cells, approximately 8 km^2 at the equator [34]. During our GIS processing and analysis the real size of the watersheds had been calculated in square kilometres based on the geographical location (latitude) of cells belonging to each basin. The metadata of GRDC gauging stations (catchment size and mean annual discharge) was applied as control data. Additionally the channel gradient and surface slope gradient have been derived from the SRTM global elevation dataset [35].

3.4.2. Suitability mapping, distance analysis and cost estimation

Based on the description of almost 8000 stations globally and the hydrographical description African river data, river segments and suitable area fulfilling the following criteria had been selected as potential locations of mini hydro systems:

- permanent river (from VMAP0) [36];
- river gradient or surface gradient along the river > 1% (derived from SRTM30) [37];
- catchment size > 100 km^2 (calculation based on HydroSHEDS) [38];
- mean annual stream flow > 4 m^3/s (GRDC) [39].

The processed and combined GIS data resulted in a binary map of suitable and non-suitable areas (Fig. 7a). The estimation of electricity production cost based on a typical production cost calculation (15 cEur/kWh, see Table 2) combined with the distance from the closest suitable river section. The lifetime production costs has been calculated taken into account the average life time, the investment and operation cost of the hydropower plants projects in Africa. The grid extension cost from the closest permanent river to a local grid has been established at 2.5 cEur/kWh/km. The hydropower generator has been determined to produce at least as much energy output as a 15 kW PV array would produce in the same location (with the additional advantage of continuous production).The result map shows the financial differences within the area suitable for electricity production using small scale hydro power systems (Fig. 7b).

3.5. Finding the most economic electricity generation option

The cost of electricity delivered has been computed for each pixel of the African continent for four options: extension of the grid from the closest existing network, hydropower including the extension of a local grid from the closest permanent river section, off-grid PV system and stand-alone diesel generator. Based on the power generation costs belonging to each energy source the minimum price can be defined for each geographic location by the following formula:

$$[\mathrm{COST\_MINIMUM}] = \mathrm{minimum}(\mathrm{cost\_diesel}, \mathrm{cost\_hydro}, \mathrm{cost\_gridext}, \mathrm{cost\_pvkwh}) \quad (3)$$

At this point it is possible to retrieve the generation type that has the lowest production costs for each location. Theoretically several classes could be generated including all the combinations of the different sources (e.g., PV and hydro), but in practice the four sources are spatially clearly distributed. Fig. 8 shows the most economic option for the same area visualised in Fig. 7, and Fig. 9 shows the results covering the African continent for 2010 and 2012.

4. Reshaping the energy landscape: the least-cost options for rural energy services in Africa

The results of the spatial analysis demonstrates that there are a number of energy mix options accessible to rural communities, ranging from diesel generators to solar and hydro resources that is already managed by some of these communities [6,40].

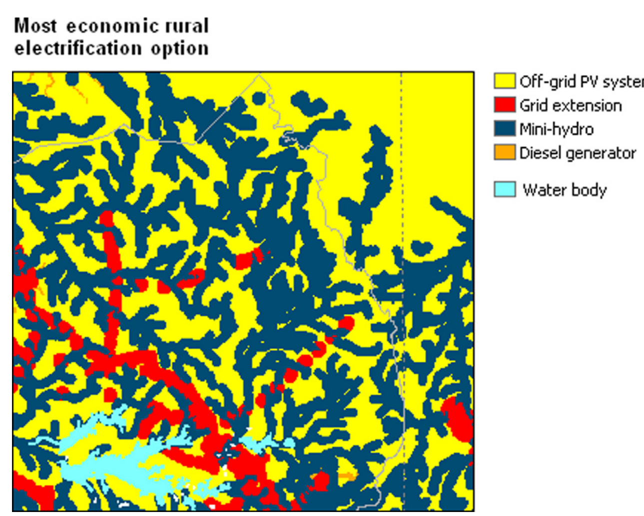

Fig. 8. The modelled most economic rural electrification option.

Table 2
Unit cost calculation for small-scale hydropower production.

	Year of investment	Annual cost from the year 1 to 10
Investment cost (€/kW)	4650	
Standard system size (kW), corresponding to the PV and diesel calculations	15	
Annual investment and O&M costs/year (€/year)	69,750	6975
Present value of investment (discount rate: 5%)	117,723	
Annual production (kWh) assuming 60% system efficiency	78,840	
Overall production during 10 years		788,400
Calculated unit costs (€/kWh)	0.149	

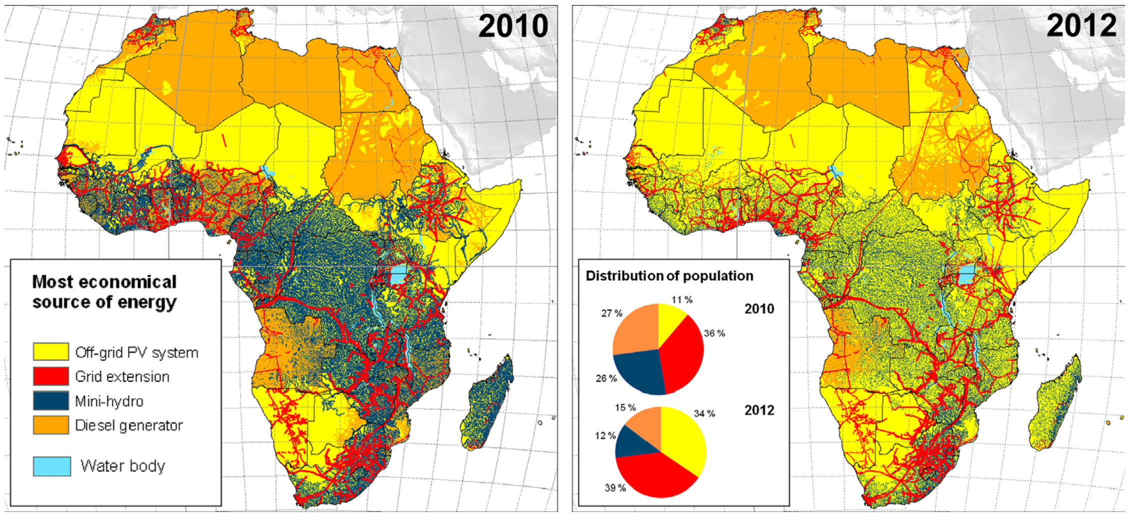

Fig. 9. Regions where grid extension may prove to be the most economic option (reddish lines) are limited to high population density regions close to the already existing grid. But overall, distributed power generation (shown in yellow for PV, orange for diesel gensets, and blue for mini hydro) – as contrasted to grid extension – is a more viable option for many communities in vast regions of Africa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

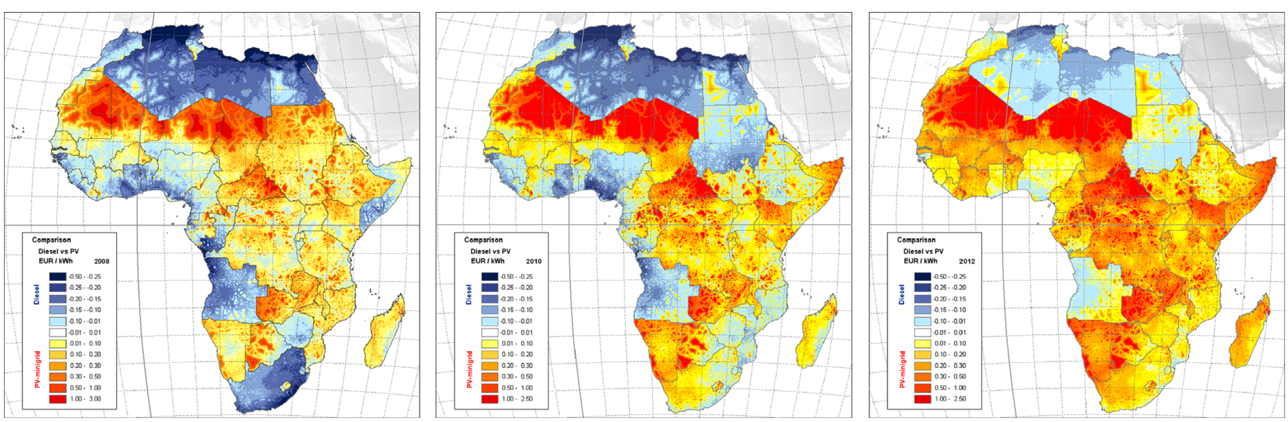

Fig. 10. Change over time of diesel and PV costs, annual snapshots of years 2008, 2010 and 2012.

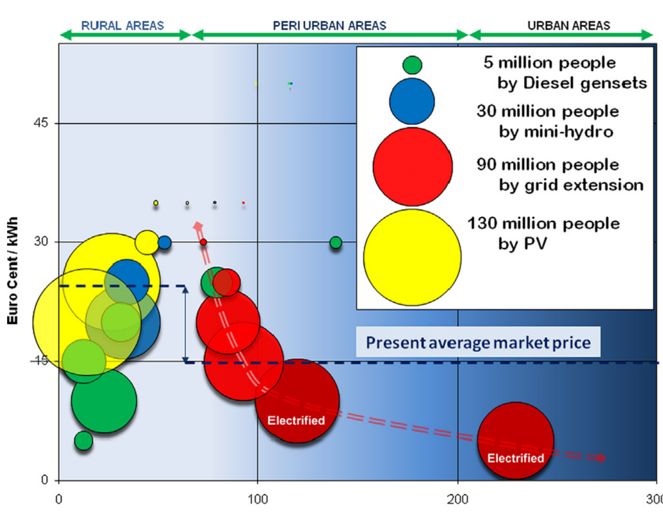

Fig. 11. Size of population potentially served by the least-cost electricity option depending on population density (urban, peri-urban and rural regions).

The research question was which energy options can be developed effectively on a local decentralised basis and how to determine which are the best options (or combination thereof) that can provide cost-effective energy services depending on the indigenous resources. The methodology has helped distinguishing the least-cost options (the so called 'low hanging fruits' [41,42]) from the more expensive ones. The analysis does not only reveal the significant potential of the renewable energy based rural electrification technologies, but also makes it possible to compare the necessary financial contribution from the consumers between the full energy service scenarios. The financial burden of reaching the total population can be approximated assuming the implementation of the least cost technology portfolio presented in this paper.

Most new investments in energy solutions in Africa have been focusing on large capital projects (i.e. Gigawatt hydro projects, extension of high-voltage transmission lines). The World Bank projects that of the USD 93 billion needed to improve Africa's infrastructure, almost half is needed to boost the continent's power supply [43]. The financing need for the installation of new power generation capacity is calculated at the rate of seven

times the annual average of the last 10 years. At the same time, the majority of sub-Saharan countries suffer from chronic power shortages, almost 40% of the African grid was built or refurbished more than 30 years ago, and it is estimated that USD 18 billion are needed only for the renovation of the existing grid [43].

On the other hand, the global renewable energy investment (i.e. total private and public investment) has increased six-fold, from USD 41 billion in 2004 to USD 268 billion in 2010 [43]. Parallel to this investment boost, development assistance for renewable energy systems in developing countries has also increased in recent years (i.e. in 2010 Africa multiplied from the previous year by almost five-fold to USD 3.6 billion) but at a much lower scale [44,45]. The International Energy Agency estimates 3% of the global energy investment is needed in order to achieve the 'International Year of Sustainable Energy for All' (SE4ALL) initiative goals [1]. So far USD 360 billion is committed by 50 countries, out of which USD 32 billion is dedicated for energy access targets.

To analyse the economics of development and long-term support perspective, we estimated the yearly cost (including investment repayment) that the consumers would pay in case the SE4ALL targets would be met. The calculations are based on the optimal rural electrification scenario given by the above described methodology. Our results indicate that all the consumers served under the least-cost off-grid portfolio would pay 20% more than if consumers would be served at the present cost levels (including grid cost). This grid cost component has been calculated under a conservative assumption where production costs and the transmission costs are the average costs for highly populated areas calculated for countries where blackout time is lower than 5% and average lifetime is lower than 30 years. However, closer examination of our results (see Fig. 11) shows that the transmission cost component for connecting the scattered rural population would be much higher than the present grid served consumers, therefore the yearly grid extension costs would be much higher than this conservative assumption.

5. Policy and financial implications

At the regional policy level the results of this GIS application can be explored in two fields. Firstly one to study the dynamisms of technology competitiveness due to the experienced changes in fossil fuel subsidy and reduction in technology costs in PV. Secondly we show the trend which energy production technologies are the most competitive ones in the various locations in Africa characterised by different resource parameters.

5.1. Effects of subsidy schemes

Important adverse effects of the fossil fuel subsidies can be revealed by applying the mapping methodology for the time series of the years 2008, 2010 and 2012. Fig. 10 shows the change over time of the comparison between PV and diesel minigrid costs caused by the change in PV system costs and diesel prices. The four years development indicates critical changes: the PV module price dropped by more than 50% while diesel price gradually increased due to the international crude oil price and the removal of diesel subsidies in many countries resulted that the PV as the least-cost option for rural electrification in Africa took over the dominance by 2012.

The results of the spatial techno-economic analysis reveal how sensitive the rural electrification costs are to diesel prices and its price evolution. The homogeneous colour of the countries that give generous fossil fuel subsidies are delineated by the borders rather than by local energy resources (i.e. solar irradiation) or by the already existing infrastructure (grid, road, distance to closest refuelling station). The fossil fuel subsidy has a very dramatic crowding-out effect: by making the diesel option cheap, it prevents the development of other options.

In many African countries the discontinuation of diesel subsidies has strongly reduced the competiveness of the diesel option and as a consequence it is replaced by other economically more competitive local resource. In the same way that most oil-producing countries have decided to subsidise diesel due to various social-economic factors, subsidising renewable sources could also be considered to support other off-grid technologies (for example in the form of feed-in-tariffs) to not distort the emerging rural electrification market [46]. If this policy gains more momentum the photovoltaic option could become the more favourable option in most of the remote areas [47].

5.2. Sustainable policy to find the balance between the off grid and grid extension options

Recent policy analyses [2,41] emphasise that transitioning to a sustainable energy system in Africa requires a mix of short- and long-term policies to overcome the political difficulty of implementation. These difficulties have to be compared with the potential benefits. A feasible implementation of rural electrification with moderate political difficulties [2] would imply investments on low-cost clean energy supply (depicted by the lower positioned yellow and blue bubbles in Fig. 11) and the removal of the diesel subsidies (see evolution in Fig. 10).

The trade-offs between immediate versus more long-term benefits is depicted by the analysis in Fig. 11. It is derived from the least cost technology map to show which technology is the most suitable depending on population density. The results of the analysis highlight the importance of taking into account the potential of all the local energy sources in the rural electrification policy planning process. To reach high electrification rates in Sub-Saharan Africa would not be feasible relying only on technologies which require a functioning central grid (as most big power plants do). The analysis shows how introducing all viable options of distributed generation can bring closer to realise the least-cost portfolio. It also clearly shows that the least-cost solution is not a one-size-fits-all solution: it is a mixture of different technologies. Some can perform better in certain locations and be less attractive under other conditions. The already electrified population clusters are those cheapest to reach (dark red bubbles): highly populated regions where the grid extension is economically viable or those living close to transport network for diesel supply. It can be observed clearly that for low density population areas decentralised options (diesel genset, hydro and PV) are the least-cost for rural electrification.

Setting up international financial schemes that support project developments as well as national energy priorities needs coordination between the regional and national donor institutions. Geographical information sources (such as the presented results) can be combined with information on economic and social factors to better inform policy decisions, and can help professionals, energy planners, and non-governmental organisations to characterise the potential of different forms of energy to provide off-grid electricity in sub-Saharan Africa and determine the least-cost technology options.

6. Conclusions. A Roadmap to support universal access to electricity

The results of the present analysis show the unique opportunity to move forward in energising Africa without necessarily repeating all previous development stages (installing large size power plants and extending the grid to new consumers).

Using an innovative suite of spatial tools, a set of alternative energy planning options have been derived that not only address the existing rural energy gap but also in many areas offer an alternative to projects requiring large capital inflows and limits fossil fuel dependence.

The presented multi-layered analysis using a wide range of geographical information sources has shown that when access to electricity is considered as a policy priority, grid extension should not be the exclusive option; neither from a sustainable perspective nor from cost-effective point of view. The diesel gensets which have been the principal off-grid option of the past maintains a role but to a much lesser extent than before: removing diesel subsidies will render this option less important. Only a mixture of different portfolio elements containing an adequate share of distributed local renewable energy options can offer a long-term solution for energy access in rural communities such as those in sub-Saharan Africa.

Integration of development agendas into energy planning has been limited, in part, by a lack of integrated energy planning tools necessary for prioritising the most suitable options in each region. The set of tools presented and results based on those analyses can support decision and policy makers to plan for the least-cost rural electrification options while also adapting to the most effective way to reduce energy poverty.

Reaching universal access to modern energy services will require action by all sectors to shape the policy and investment decisions. Important decisions on the allocations of development funds targeting energy are ongoing and will be made in the near future. The spatial tool presented can support planning the massive electricity infrastructure requirements that are needed to reach universal energy access. Whether financing large-scale or small decentralised energy projects have more sustainable impacts on the energy access will become a central issue.

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